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Cressie, Noel, A.

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Ohio State University Research Foundation
1960 Kenny Road
Columbus OH 43210-1063

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Office of Naval Research
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14. ABSTRACT

One of the key tools that a commander can use to understand and control the battlespace is a map. The danger potential of (mobile) enemy weapons is a functional of the location of the weapons, their accuracy, and their firepower. In this research, we develop statistically optimal maps that show danger potential. Producing such maps requires estimates of the weapons' locations at the current time. As the weapons move, the estimated map evolves dynamically, as do measures of its uncertainty. Forecasting the map is a very important problem, which we address through a spatial statistical method that forecasts waypoints.

15. SUBJECT TERMS

Bayesian analysis; C2; danger field; kriging; particle filtering; waypoint

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FINAL TECHNICAL REPORT
"SPATIAL STATISTICS FOR COMMAND AND CONTROL"

Grant No.: N00014-02-1-0052

Period of Award 10/1/02 – 6/30/05

PI Name: Noel A. Cressie

Address: Department of Statistics
The Ohio State University
1958 Neil Avenue
Columbus OH 43210-1247

Phone Number: 614-292-5194

Fax Number: 614-292-2096

E-mail Address: ncressie@stat.ohio-state.edu

Objectives

One of the key tools that a commander can use to understand and control the battlespace is a map. The danger potential of (mobile) enemy weapons is a functional of the location of the weapons, their accuracy, and their firepower. The first objective is to develop statistically optimal maps that show danger potential. Producing such maps requires estimates of the weapons' locations at the current time. As the weapons move, the estimated map evolves dynamically, as do measures of its uncertainty. The second objective is to develop statistically optimal dynamic maps and their associated uncertainty. Forecasting the map is a very important problem; then the third objective is to develop a spatial statistical method to forecast waypoints.

Impact/Applications

We have developed two web sites at The Ohio State University:
www.stat.ohio-state.edu/~C2
considers probability and statistics in Command and Control.
www.stat.ohio-state.edu/~sses/collab_ozone.php
demonstrates a multi-resolution mapping approach that fills in missing data and smooths out noise. The application is to global mapping of total column ozone.

Although not tied to the grant, during the period of the grant a contract was signed to carry out work for a team at SPAWAR, San Diego. This was very focused work on Behavioral and Geopological Tendencies, namely how to detect if a country's defensive position has changed as a reaction to changing threat levels.

Personnel

Principal Investigator:	Noel Cressie, Ph.D.
Statistical Scientist:	Mark Irwin, Ph.D.
Postdoctoral Fellow:	John Kornak, Ph.D.
Research Assistants:	Gardar Johannesson Martina Pavlicova Yonggang Yao
Visiting Professor:	Hsin-Cheng Huang, Ph.D. (Academia Sinica, Taiwan)

Technical Approach

When quantifying problems in command and control (C2), it helps to consider the abstract concept of a battlespace. A battlespace is a highly dynamic environment composed of a large number of distinct components, including both friendly and enemy military resources, weather, and terrain. Each of these components in turn can be thought of as being composed of a number of smaller elements. *Danger potential* is defined to be the expected damage that a given set of

weapons can inflict upon a particular location in space. Specifically, denote $f(\mathbf{w}_{k1}|\mathbf{s},\mathbf{w}_k)$ as the probability density function of an impact at location $\mathbf{w}_{k1}$, given the weapon is located at $\mathbf{w}_k$ and is aiming at location $\mathbf{s}$. Then we can define the danger potential generated by a single weapon element at location $\mathbf{w}_k$ as the expected damage at any location $\mathbf{s}$:

$$g(\mathbf{s};\mathbf{w}_k) \equiv \int_{\mathbf{w}_{k1}} \delta(r_{\mathbf{s}},\mathbf{w}_{k1}) f(\mathbf{w}_{k1} \mid \mathbf{s},\mathbf{w}_k) d\mathbf{w}_{k1}; \qquad \mathbf{s} \in \mathrm{D}. \tag{1}$$

For multiple weapons, the danger potential is assumed to be additive. In the initial conceptualization, the data are locations of military constituents, observed with error. Given the data, the objective is to estimate and map the true danger potential everywhere in the spatial region of interest. Since the battlespace is highly dynamic, so too is the danger-potential map. Additional details on this research can be found in Wendt et al. (2001).

In a C2 setting, any summary of the danger surface can be interesting to the battlespace commander (e.g., hotspots, representing high danger). This generally leads to nonlinear functionals of surfaces that can be predicted through variants of Kalman filters. Covariance-matching constrained kriging (e.g., Cressie and Johannesson, 2001; Aldworth and Cressie, 2003) gives predictors of such functionals that are approximately optimal.

Forecasting battlespace maps at future time points would be extremely useful to the battle commander. One approach for forecasting the location of a mobile enemy weapon is *waypoint analysis*. A waypoint is simply a set of coordinates in space and time describing a location that a mobile weapon is attempting to reach by a given time. Assuming that enemy weapons have a specific target in mind can provide the investigator additional information about which path they are likely to travel along, and thus about the danger-potential field at future time points.

In developing statistical techniques for waypoint analysis, we start with the simple assumption of an unknown single waypoint. In order to forecast a waypoint, a key set of assumptions must be made regarding how the object moves. We assume that at each time point, the object revises its intended path in order to reach the waypoint. A simple assumption is that these intended paths will involve movement at constant speed in a straight line, from the spatial-temporal position at which the intended path was revised, to the spatial-temporal location of the waypoint. We recognize that, regardless of intention, the actual path will vary from the intended path, which we model with random error. We examine not only the location of a weapon heading toward a waypoint over time, but the speed and angle at which it is traveling at each time point. We use Bayesian techniques to provide a posterior distribution of the (future) waypoint given (current and past) space-time data on the enemy weapon's location.

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Aldworth, J. and Cressie, N. (2003). Prediction of nonlinear spatial functionals. *Journal of Statistical Planning and Inference*, **112**, 3-41.

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Results

A considerable number of presentations and publications occurred during the course of the grant.

Presentations related to grant-supported research.

2002

October	Presented a keynote address at ASA Section for Statistics and the Environment Conference on Spatial Statistics; "Spatial statistics in the presence of location error"
	Co-presented (with Mark Irwin) an invited paper at Eighth U.S. Army Conferece on Applied Statistics, Raleigh, NC; "Particle filtering and spatial prediction in the battlespace"
November	Presented an invited paper (with G. Johannesson) at Fourth European Conference on Geostatistics for Environmental Applications, Barcelona, Spain; "Spatial variance-covariance estimation in multi-resolution models"

2003

January	Presented an invited paper at Symposium on Environmental Statistics, Ghent, Belgium; "Spatial statistical analysis of environmental data in the presence of location error"
March	Presented an invited paper at GREMAQ, University of Toulouse 1, Toulouse, France; "Variance-covariance modeling and estimation for multi-resolution spatial models"
	Presented an invited paper at ENAR Biometric Society Spring Meeting, Tampa, FL; "Variance-covariance modeling and estimation for multi-resolution spatial models"
June	Presented an invited paper at SAMSI/NCAR Workshop on Spatio-Temporal Statistics, Boulder, CO; "Dynamic multi-resolution spatial models"
	Presented an invited apaper at Journee Statistique et Econometrie du GREMAQ Workshop, University of Toulouse 1, Toulouse, France; "Dynamic multi-resolution spatial models"

September	Presented a keynote address at 2003 IEEE Workshop on Statistical Signal Processing, St. Louis, MO; "Nonparametric hypothesis testing for a spatial signal"
December	Presented an invited paper at AIC2003: Science of Modeling, Yokohama, Japan; "Dynamic multi-resolution spatial models"

2004

March	Presented an invited paper at SPRUCE Advanced Workshop on Spatial/Temporal Models and Methods, Costa do Estoril, Portugal; "Dynamic multi-resolution spatial models"
April	Presented an invited paper at Workshop on Uncertainty, Complexity and Predictive Reliability of Environmental/Biological Models, University of Nottingham, Nottingham, UK; "Methods for adjusting spatial inference in the presence of data-location error"
June	Presented the keynote address at 2004 Graybill Conference, Fort Collins, CO; "Dynamic multi-resolution spatial models"
July	Presented an invited paper at Australian Statistical Conference 2004; "Spatial statistics in the presence of location error"
September	Presented an invited paper (with M. Pavlicova) at Seventh International Geostatistics Congress, Banff, Canada; "Permanence of lognormality: Bias adjustment and kriging variances"
October	Presented an invited paper (with J. Zhang and P. Craigmile) at Fifth European Conference on Geostatistics for Environmental Applications, Neuchatel, Switzerland; "Geostatistical prediction of spatial extremes and their extent"

2005

June	Presented an invited paper at SAMSI Workshop on Bridging Statistical Approaches and Sequential Data Assimilation, Research Triangle Park, NC; "Data assimilation using multi-resolution spatio-temporal models"

Articles written/published related to grant-supported research.

Refereed Articles:

Cressie, N. and Pavlicova, M. (2002). Calibrated spatial moving average simulations. *Statistical Modelling*, **2**, 267-279.

Irwin, M. E., Cressie, N. and Johannesson, G. (2002). Spatial-temporal nonlinear filtering based on hierarchical statistical models (with discussion). *Test*, **11**, 249-302.

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Johannesson, G. and Cressie, N. (2004). Finding large-scale spatial trends in massive, global, environmental datasets. *Environmetrics*, **15**, 1-44.

Ver Hoef, J. M., Cressie, N., and Barry, R. P. (2004). Flexible spatial models based on the Fast Fourier Transform (FFT) for cokriging. *Journal of Computational and Graphical Statistics*, **13**, 265-282.

Wendt, D. A., Irwin, M. E., and Cressie, N. (2004). Waypoint analysis for command and control. *Naval Research Logistics*, **51**, 1045-1067.

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Tzeng, S., Huang, H.-C., and Cressie, N. (2005). A fast, optimal spatial-prediction method for massive datasets. *Journal of the American Statistical Association*, **100**, 1343-1357.

Craigmile, P. F., Cressie, N., Santner, T. J., and Rao, Y. (2006). A loss function approach to identifying environmental exceedances. *Extremes*, forthcoming.

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Pavlicova, M., Cressie, N., and Santner, T. J. (2006). Testing for activation in data from FMRI experiments. *Journal of Data Science*, **4**, forthcoming.

Sain, S. and Cressie, N. (2006). A spatial model for multivariate lattice data. *Journal of Econometrics*, forthcoming.